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13. ABSTRACT *(Maximum 200 words)*

The goal of the research reported here was the development of a circuit-based modeling procedure for both the passive and active components of a quasi-optical power combiner. Contributions include the development of a multi-port equivalent circuit of a multi-element quasi-optical power combiner. Excellent agreement with experimental results was obtained. Mount independent techniques were also developed for characterizing two terminal active ~~~

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QUASI-OPTICAL POWER COMBINING OF SOLID STATE MILLIMETER-WAVE SOURCES: A PROPOSAL FOR GRADUATE FELLOWSHIP

FINAL REPORT

MICHAEL B. STEER

SEPTEMBER 3, 1992

U.S. ARMY RESEARCH OFFICE

DAAL03-89-G-0030

NORTH CAROLINA STATE UNIVERSITY

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1 Statement of the Problem Studied

The goal of the research reported was the development of a circuit-based modeling procedure for quasi-optical power combiners. The work focused on the modeling of a quasi-optical cavity with multiple sources and on developing techniques for experimentally extracting the nonlinear models of two terminal active devices.

2 Summary of the Most Important Results

The thrust of the work in this project has been the development of a circuit level simulation capability and a design methodology for quasi-optical power combiners. This has involved work on three fronts:

1. Model development for the quasi-optical cavity.
2. IMPATT diode model development
3. Preliminary simulator development for simulating multiple coupled oscillators.

The work is best described in full in six papers previously submitted as reprint reports to the USARO under this grant. In this final report the abstracts and major results of this work are reported.

2.1 Quasi-Optical Cavity Model Development

Described in the manuscript "Impedance Matrix Of An Antenna Array In A Quasi-Optical Resonator" by P. L. Heron, G. P. Monahan, J. W. Mink, F. W. Schwering, and M. B. Steer, submitted for publication to the IEEE Trans on. Microwave Theory and Techniques.

2.1.1 Abstract

The power from numerous millimeter wave solid-state sources can be efficiently combined using quasi-optical techniques. One such technique is to place an array of active radiating sources within a quasi-optical resonator. The driving point impedance of each antenna is strongly effected by the presence of all other active antennas as well as by the mode structure and Q of the resonator. In this paper the impedance matrix for an array of antennas radiating into a plano-concave open resonator is determined through use of the Lorentz integral. The resulting expressions include the effect of diffraction loss and are valid for arbitrary reflector spacing, source frequency, array location and geometry. The result can be used to impedance match each active source to its antenna and thus facilitate design of an efficient power combining system. Simulations using the impedance matrix in conjunction with an antenna impedance model are compared with two-port measurements.

2.1.2 Summary

Quasi-optical techniques have been recognized as an attractive means for combining power from numerous solid-state millimeter-wave sources. Power combining is accomplished in free space through superposition of the fields produced by individual radiators which are either globally or locally phase locked. Quasi-optical power combiners have been constructed using a variety of active sources including MESFET's, IMPATT diodes, Gunn devices, and resonant tunneling diodes (RTD's). Various radiating elements have also been used including patch antennas, slot antennas, and open ended waveguide cavities. Several techniques are used to phase lock the individual oscillators, the locking being eitber global or local in nature. Combiners which lock oscillators through direct radiation from antennas are referred to as direct-radiation-coupled (DRC) combiners. Those whicb attain locking through the mode structure of a quasi-optical cavity are termed as being cavity- or resonator-coupled (RC) combiners. Both DRC and RC combiners utilize global coupling as each active element affects the driving point impedance of many otber devices. The phase locking of RC combiners is more global in nature as the radiation from any one active device is distributed over the entire array of sources due to the resonator mode structure. Tbe interaction in DRC combiners is greatest for nearest neighbors and the effect of one radiating element on the otbers is reduced with device separation. Circuit coupled (CC) power combiners achieve locking through microstrip transmission lines or other circuit elements. Sucb combiners are usually locally locked. Any of these combiner types can be self locking, or be injection locked by an external signal.

DRC combiners have the simplest structure, but the individual oscillators must be carefully designed to be nearly identical. This is necessary because the relatively weak field interaction between radiators results in a small oscillator locking bandwidth. Broadside radiation can be achieved with an in-phase oscillation regime, whicb is attained if tbe inter-radiator spacing is λ_0. This spacing results in grating lobes in the radiation pattern and also places constraints on tbe maximum area density of oscillators. The power combiner performance degrades if a single oscillating element fails due to the relatively local nature of the coupling. Circuit coupled combiners can be analyzed and designed using existing simulators for planar microwave circuit analysis.

RC and DRC quasi-optical combiners use similar planar circuits. The added resonant cavity of the RC combiner requires precise control of reflector spacing and curvature. There are, however, several advantages to using resonator coupling. Due to the resonator mode structure, inter-element spacing is arbitrary thus oscillator element density can be maximized. Phase locking is truly global in nature whicb can result in relative immunity of combiner performance to device failure. Furthermore, the strong field levels inside the cavity allow for tbe use of more compact sub-resonant antennas. The cavity field interactions also result in larger locking bandwidth, thus the individual oscillator tolerances can be relaxed as compared witb a DRC scheme. Open resonators can also produce a bighly focused radiation pattern.

Mink[1] studied an array of filamentary current sources radiating into a plano-concave open resonator. This was the first theoretical investigation of power combining using a source array in a quasi-optical resonator. The results are applicable to the design of RC quasi-optical combiners and were obtained by use of the Lorentz reciprocity tbeorem to find the coupling coefficients between the current elements and the natural short-circuit modes of the cavity. The mode coupling coefficients and the radiation resistance were determined for equal and Gaussian weighted sources under that assumption that all modes resonated at a single frequency and tbat the resonator Q was high.

The objective here was to derive a circuit level model based upon field calculations for an antenna array radiating into a plano-concave resonator. RC power combiner design can then be accomplished by using the model in conjunction with a simulator that is capable of modeling active devices and performing oscillator analysis. The source array impedance was determined employing the same techniques as uscd by Mink. The method of analysis is extended to calculate complex impedance for operation at arbitrary frequency and resonator

[1] J. W. Mink, "Quasi-Optical Power Combining of Solid-State Millimeter-Wave Sources," *IEEE Trans on Microwave Theory and Tech.*, vol MTT-34 Feb, 1986, pp. 273-279.

spacing and is also valid for cavities having increased output power coupling. A specific resonator type and antenna configuration is considered but the concepts are applicable in general.

The result of the work is an impedance matrix coupling the radiating elements in a quasi-optical cavity. An example of the accuracy of the modeling capability is shown in Fig. 1 where measured and calculated coupling impedance between two filamentary antennas are compared. Similar results were obtained for other modes and for self impedances.

2.2 Active Device Characterization

The work is described in two papers previously submitted as preprint reports under this contract: "Characterization of Diodes in a Coaxial Measurement System" by M.B. Steer and R.G. Hicks, published in the 1991 International Microwave Symposium Digest, and "Diode characterization in a coaxial mount" by M.B. Steer (accepted for publication in the International Journal on Microwave and Millimeter Wave Computer Aided Engineering). The aim of this work was to develop mount independent diode models for use in a simulation of a quasi-optical power combining system. We have completed the theoretical development of the diode characterization technique and models for IMPATT diodes can be developed.

2.2.1 Summary: "Characterization of Diodes in a Coaxial Measurement System"

A method is reported for experimentally characterizing packaged microwave diodes with respect to their outer cylindrical surface. The diode is mounted coaxial with the center conductor of a coaxial line and radial transmission line theory is used to determine the impedance of dummy diode packages used in calibration. The diode equivalent circuit thus developed is suited to the modeling of a diode mounted in a microstrip patch mount. Experimental characterization of a varactor diode and of a mixer diode were reported.

2.2.2 Summary: "Diode Characterization in a Coaxial Mount"

The above technique for experimentally characterizing packaged microwave diodes mounted in a coaxial test fixture is investigated. It is demonstrated that the fields surrounding the diode and the calibration packages are adequately developed to provide an accurate diode equivalent circuit model for use in computer aided design.

The mount used is shown in Fig. 2 where the radial fields in the region surrounding the diode are enhanced by the presence of the coaxial slug. The mount is calibrated using a standard three load calibration technique using the dummy packages shown in Fig. 3.

2.3 Quasi-optical Power Combiner Simulator Development.

Initial development of a transient quasi-optical power combining simulator has been accomplished. The work is described in "Simulation of Microwave and Millimeter-Wave Oscillators, Present Capability and Future Directions," by M.B. Steer, 1992 Workshop on Integrated Nonlinear Microwave and Millimeterwave Circuits. This paper describes a preliminary simulator for the simulation of th transient performance of a quasi-optical oscillator with a single radiating element. However the modeling used in this work was not fully developed. Before this work can be used to simulate an actual quasi-optical power-combiner problems relating to Fourier transforming the frequency domain cavity impedance matrix need to be resolved and the cavity modeling work applied to realistic antennas. This work is being undertaken

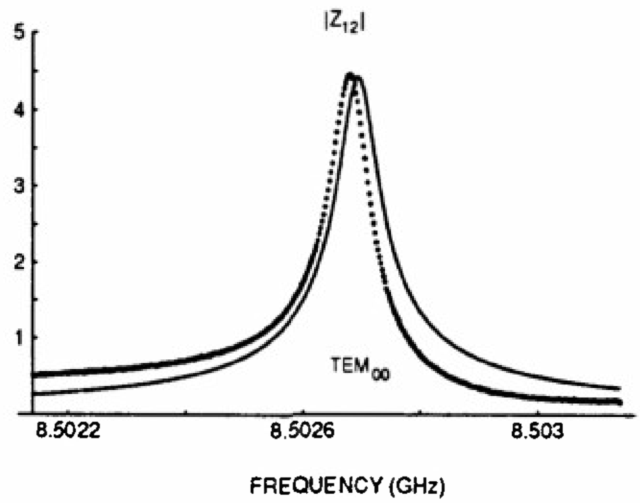

Figure 1:

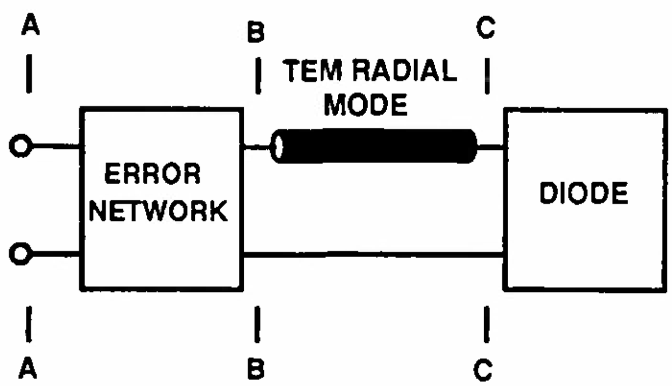

Figure 2:

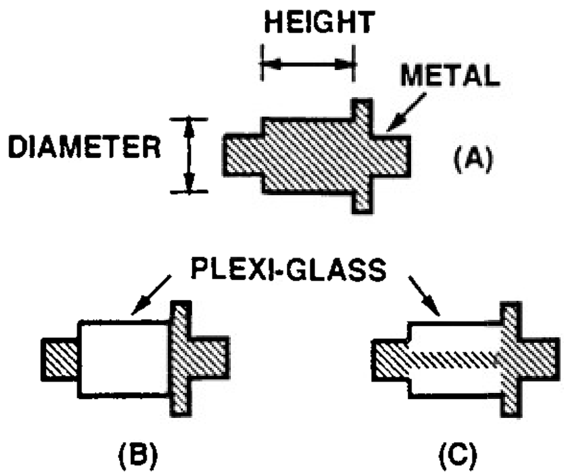

Figure 3:

in a continuation contract. However the results shown in Figs. 4 and 5 for a single IMPATT diode in a quasi-optical cavity indicate the feasibility of our strategy to provide circuit level modeling, simulation, and computer assisted design capability for quasi-optical systems.

2.4 Harmonic Balance Analysis of Quasi-optical Power Combining Oscillators

Harmonic balance analysis of quasi-optical power combining oscillators is a focus of the continuation contract but we have completed (and transferred to the microwave CAD industry) an harmonic balance based oscillator simulator. We intend applying this to the steady-state simulation of quasi-optical power combiners in the continuation contract. Two aspects of this work were supported by this contract and are described in "Jacobian calculation using the multidimensional fast Fourier transform in the harmonic balance analysis of nonlinear microwave circuits," by P.L. Heron, and M.B. Steer, *IEEE Trans. Microwave Theory Tech.*, April 1990, pp. 429-431, and "Control of Aliasing in Harmonic Balance Analysis of Nonlinear Circuits," by P.L. Heron, C.R. Chang and M.B. Steer, *1989 IEEE MTT-S International Microwave Symposium Digest*, June 1989. Both papers discuss issues that are particularly crucial in the simulation of high Q oscillators such as quasi-optical power combining oscillators.

2.4.1 Abstract: Jacobian Calculation Using the Multidimensional Fast Fourier Transform in the Harmonic Balance Analysis of Nonlinear Microwave Circuits

A technique is developed whereby the gradient of frequency domain simulation variables may be analytically determined using time domain derivative information and the multidimensional fast Fourier transform. It is shown that this technique can be efficiently implemented when a circuit is driven by any number of incommensurate input frequencies. A harmonic balance simulator is constructed which uses this technique to determine the entries of the Jacobian matrix which are needed in a quasi-Newton iteration scheme. A significant reduction of simulation time is observed when compared with a harmonic balance simulator that

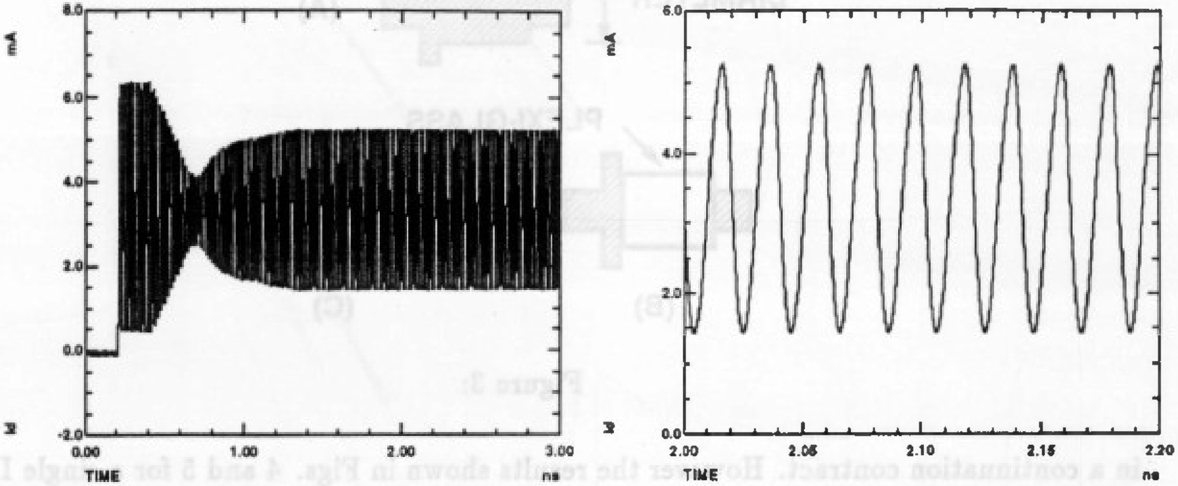

Figure 4: Current through IMPATT diode.

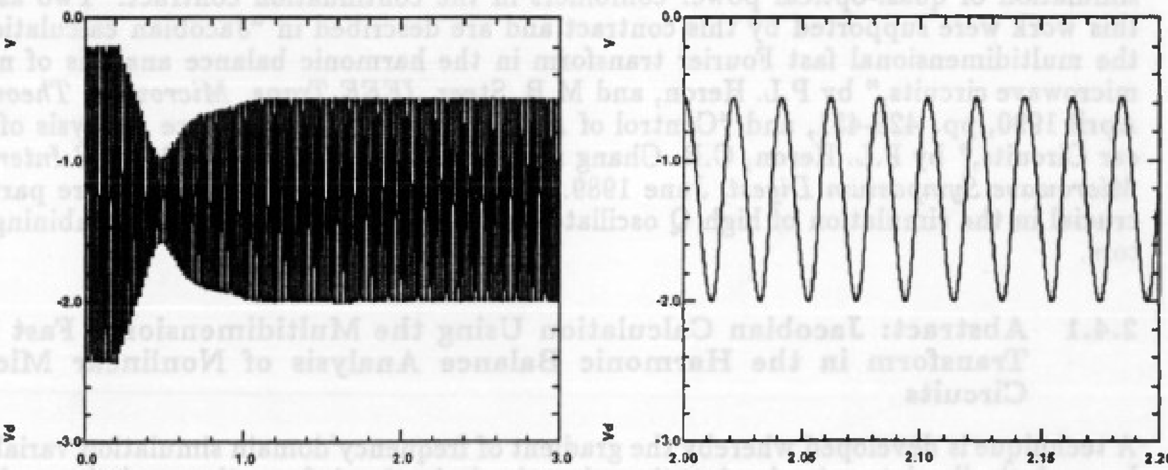

Figure 5: Voltage across IMPATT diode terminals

uses matrix multiplication based transforms.

2.4.2 Abstract: Control of Aliasing in Harmonic Balance Analysis of Nonlinear Circuits

The simulation of nonlinear microwave circuits using harmonic balance requires Fourier transformation to interface the frequency domain analysis of the linear subcircuits with the time domain analysis of the nonlinear subcircuits. Prevention of aliasing in the Fourier transform requires that a larger frequency set be used than is required to accurately represent the nonlinear response in the harmonic balance procedure. Here a dual frequency set harmonic balance analysis scheme is presented where a larger frequency set is used in the Fourier transformation and a smaller set in the harmonic balance iterations. This procedure reduces memory requirements and computation time while maintaining accuracy.

3 List of Publications

1. P.L. Heron, J.W. Mink, G.P. Monahan, F.W. Schwering and M.B. Steer "Impedance matrix of a dipole array in a quasi-optical resonator," *Submitted for Publication.*

2. M.B. Steer, "Diode characterization in a coaxial mount," *International Journal on Microwave and Millimeter Wave Computer Aided Engineering. In Press.*

3. M.B. Steer and R.G. Hicks, "Characterization of Diodes in a Coaxial Measurement System," in *1991 International Microwave Symposium Digest*, pp. 173-176, June 1991.

4. M.B. Steer, "Simulation of Microwave and Millimeter-Wave Oscillators, Present Capability and Future Directions," 1992 Workshop on Integrated Nonlinear Microwave and Millimeterwave Circuits, October 1992 (invited

5. P.L. Heron, and M.B. Steer, "Jacobian calculation using the multidimensional fast Fourier transform in the harmonic balance analysis of nonlinear microwave circuits," *IEEE Trans. Microwave Theory Tech.*, April 1990, pp. 429-431.

6. P.L. Heron, C.R. Chang and M.B. Steer, "Control of Aliasing in Harmonic Balance Analysis of Nonlinear Circuits," *1989 IEEE MTT-S International Microwave Symposium Digest*, June 1989.

4 List of Participating Scientific Personnel

1. Michael B. Steer, Principal Investigator.

2. Patrick L. Heron, Ph.D. Candidate, Degree expected December 1992.

3. Gregory P. Monahan, Ph.D. Candidate, Degree expected December 1993.